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A PMU-Based Three-Step Controlled Separation with Transient Stability Considerations

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Abstract— Controlled separation has been identified as one of the critical strategies to prevent a blackout of a bulk power system following a severe disturbance. To implement this critical strategy, optimal splitting points have to be identified subject to a series of steady-state and dynamic constraints. In this paper, a systematic controlled separation with three steps is proposed to cover steady-state and dynamic constraints with PMU measurements. At the first step, the power flow tracing method is employed to pre-determine the splitting points and establish rough islands. The buses cannot be covered at the first step will be analyzed with steady-state constraints at the second step. The last step will check the transient stability during the system separation with PMU measurements. The strategies with good steady-state and dynamic performance will be identified. A test system is shown to validate the proposed method.

Index Terms-- Controlled separation, PMU, power flow tracing, steady-state constraints, three-step strategy, transient stability

I. INTRODUCTION

A severe disturbance might result in un-synchronization between different groups of generators in different areas. Controlled separation might be used to prevent a system-wide blackout of an interconnected system if other control strategies cannot terminate out-of-step of the system. Based on swinging characteristics, generators can be divided into several different groups, which determine the number of separated areas. The critical issue is to choose appropriate splitting points to guarantee steady-state and transient stability after separation.

The importance of controlled power system separation has been well recognized. Several methods were proposed in papers [1][2] to identify different coherent groups of different generators. The coherent groups, showing inherent influences between different generators, may represent the possible loss of synchronism between different generators to some extent. Coherency-based methods were presented in papers [3][4] to search splitting points. A graph method was employed to simplify complicated systems and an ordered binary decision diagram (OBDD) method was used to reduce the solution

space to find acceptable splitting points in papers [5][6]. Papers [5][6] mainly focused on steady-state constraints, i.e., the power balance. However, in real systems, separated strategies, which satisfying steady-state constraints, might also be transient instability after separation. Paper [7] proposed two threshold constraints to ensure transient stability of the separated sub-systems. However, transient stability constraints, in this work, were indirectly developed into two steady-state thresholds that may not completely represent dynamic characteristics of a system, and the values of two steady-state thresholds would be different for different systems. Considering the significance of transient stability after separation, it is necessary to provide acceptable splitting strategies, which considers dynamic constraints besides steady-state constraints.

In this paper, a PMU-based three-step controlled separation scheme with steady-state and dynamic constraints is proposed. During a controlled separation scheme that is triggered by swinging characteristics of different generators, it will be helpful if each separated area can be balanced approximately. For this task, the power flow tracing method will be used to approximately estimate the proportion of the capacity of each load supplied by each generator. Therefore, at the first step of the proposed scheme, the power flow tracing method is employed to pre-determine the areas that partial loads belong to. For the cases that some loads that are supplied by generators in different areas simultaneously, possible strategies, which satisfy acceptable power imbalance in each separated area, can be selected according to the system topology at the second step. Furthermore, inappropriate separation strategies, even with acceptable power imbalance, may also result in transient instability during separation. Therefore, at the third step, an energy-based method is used to check transient stability of each separated area based on measurements provided by PMUs, and the approximate critical energies for possible strategies are calculated off line in advance.

The paper is organized as follows. Section II describes the framework of the proposed method and corresponding techniques. Section III shows simulation results that validate the proposed method. Conclusions are presented in Section IV.

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II. THE FRAMEWORK OF THE PROPOSED CONTROLLED SEPARATION STRATEGY

Fig.1 presents the framework of the proposed controlled power system separation strategy. The whole framework includes offline analysis and online three-step analysis.

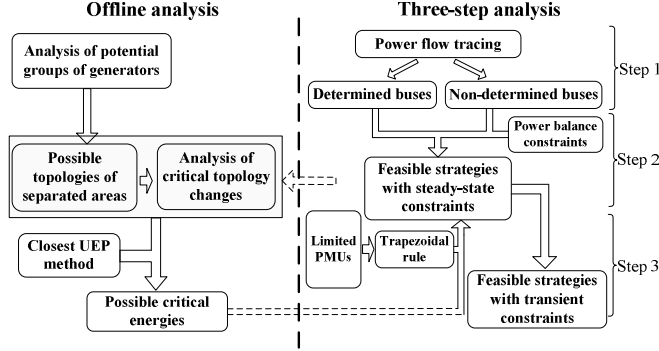


Figure 1. The framework of the proposed strategy

A. Three-Step Analysis

The three-step strategy includes 1) separating rough subsystems based on power flow tracing, 2) prioritizing possible strategies based on acceptable power imbalance, and 3) checking transient stability based on PMUs' measurements.

The first two steps involve steady-state constraints and the third step covers dynamic constraints. Based on these three steps, acceptable strategies, which satisfy steady-state and transient stability, can be identified. The detailed three steps are shown as follows.

Step 1: Separating Rough Subsystems Based on Power Flow Tracing. After splitting a system, one crucial problem is to ensure the power balance in each separated area under current outputs of generators in operation. For a certain operating condition, the power flow tracing method can approximately estimate the proportion of the power of each load supplied by each generator. For the high proportion of the power of a load, e.g., L_A , supplied by a group of generators, e.g., G_A , the load L_A can be considered to be in the area that G_A belongs to.

To estimate the proportion quickly, DC power flow is employed here. The total flow P_i through the bus i , when looking at outflows, can be presented as

$$P_i = \sum_{j \in D_i} |P_{ji}| + P_{Li} \quad i = 1, 2, \dots, N \quad (1)$$

where N is the number of buses, D_i is the set of buses supplied directly by the bus i , P_{ji} is the line flow out the bus i of the line $i-j$, P_{Li} is the load demand at the bus i . Equation (1) can be rewritten as (2) by substituting $|P_{ji}| = (|P_{ji}|/P_j) \cdot P_j$.

$$P_i - \sum_{j \in D_i} (|P_{ji}|/P_j) \cdot P_j = P_{Li} \quad i = 1, 2, \dots, N \quad (2)$$

$$\text{or } \mathbf{A}_d \mathbf{P} = \mathbf{P}_L \quad (3)$$

where \mathbf{P} is an $N \times 1$ vector of through-flows of each bus, \mathbf{P}_L is an $N \times 1$ vector of the load demand of each bus, \mathbf{A}_d is an $N \times N$ downstream distribution matrix that can be denoted as follows.

$$[\mathbf{A}_d]_{ij} = \begin{cases} 1 & \text{for } i=j \\ -|P_{ji}|/P_j & \text{for } j \in D_i \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

The output of the i th generator used to supply the load demand at the bus k can be expressed as

$$P_{Gi,Lk} = \frac{P_{Gi} P_{Lk}}{P_i} \mathbf{e}_i^T \mathbf{A}_d^{-1} \mathbf{e}_k \quad (5)$$

where \mathbf{e}_i is an $N \times 1$ vector in which the i th element is 1 and 0 elsewhere.

For loads that are completely or almost supplied by one group of generators, the areas that these loads belong to can be determined at this step. These loads can be considered as "determined loads", and the other loads can be defined as "undetermined loads".

Step 2: Prioritizing Possible Strategies Based on Acceptable Power Imbalance. For "undetermined loads", their different groupings result in different separation strategies. However, some of these strategies may violate the acceptable power imbalance in each area after separation. In addition, constraints of the network topology guarantee that the possible strategies are within the limited solution space. Usually, these strategies, which satisfy steady-state constraints, can be considered as feasible strategies. However, some strategies, satisfying steady-state constraints, may be out of step again after separation. In this paper, strategies, satisfying the acceptable power imbalance, are prioritized based on the absolute values of their power imbalance. The strategy with a less absolute value of the power imbalance has a higher priority. At the third step, transient stability of these strategies will be checked.

Step 3: Checking Transient Stability Based on PMUs' Measurements. The strategies, selected at the second step, may be out of step again after splitting the system. Therefore, it is necessary to check whether or not these strategies satisfy transient stability after separation. At the step of off line analysis, approximate critical energies for possible strategies are already calculated. At this step, initial values, i.e., rotor angles and angle speeds, when separation should be monitored by PMUs. To guarantee that the strategies satisfy the transient stability, an equivalent problem is to check whether or not the dynamic system with initial values converge to the stable equilibrium point of the dynamic system.

Consider that there may be limited PMUs installed in a power system, an implicit integration method with the

trapezoidal rule is employed to approximately estimate the unobservable state variables. The dynamic model of a system can be represented as follows.

$$\dot{\mathbf{X}} = \mathbf{f}(\mathbf{X}) \quad (6)$$

where \mathbf{X} is a vector of rotor angles and angular speeds of generators. The estimated values of unobservable variables at the time t and the observed values of observable variables at the time t and $t + \Delta t$ are used to estimate the unobservable variables in the time $t + \Delta t$ based on the implicit integration method with the trapezoidal rule [9].

B. Offline Analysis

The main task of offline analysis is to identify possible critical energies. It can be divided into following three steps.

1) *Identification of Potential Groups of Generators*: After disturbances, generators in a power system tend to form different groups with regard to slow oscillation modes [7]. Based on slow oscillation modes, different combinations of generator groups can be formed after different disturbances. For a typical operating condition, possible potential groups of generators after disturbances can be identified by slow coherency analysis or time domain simulations.

2) *Analysis of Possible Topologies and Critical Topology Changes*: Based on possible groups of generators for different typical operating conditions, possible separated areas can be established. For example, G1, G2 and G13 are in a group and G5, G8 and G11 are in another group after disturbances, shown as Fig.2. One possible scenario is to split lines 6-12, 12-10 and 15-16. One corresponding area, including G1, G2 and G13, consists of lines 1-2, 1-3, 2-4, 3-4, 4-12, 12-13 and 12-15. All possible splitting strategies can be identified under typical operating conditions.

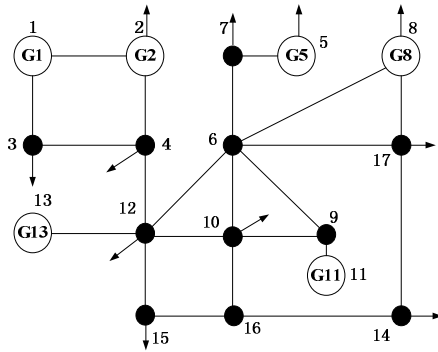


Figure 2. A system with six generators

For the separated areas, some lines and loads may be changed because of clearing disturbances or other emergency controls. For example, if the line 2-4 is out of service due to a fault, the area, including G1, G2 and G13, will not include the line 2-4. The topology is changed accordingly. The change on the topology has an influence on the dynamic characteristics of the separated systems. Actually, for a system, especially a large-scale system, many minor topology changes, e.g., one or two lines are out of service, will not have a great influence on

the dynamic characteristics of the system. For these non-critical changes, their dynamic characteristics can be approximately equivalent to those of the corresponding original topologies. For critical lines, the operating state changes can result in vast differences on dynamic characteristics. Therefore, it is necessary to identify these critical lines. Actually, critical lines are often lines that are with large power flows and close to generators. For a real system, critical lines can be identified by operators according to actual power flows.

3) *Calculation of Possible Critical Energies Based on the Closest UEP Method*: Dynamic characteristics of a system with initial values can be predicted by many methods, e.g., closest UEP, controlling UEP, BCU, BCU-Exit point. The difficulty and calculation time of different methods are also different. The closest UEP method can calculate the stability region of a dynamic system more easily compared with other methods. Therefore, the closest UEP method is employed to calculate the stability region of possible separated areas without and with critical changes. The detailed steps of calculating closest UEP of a given system are shown as follows [8].

- Find the stable equilibrium point and all type-one equilibrium points of the given possible separated system.
- Check whether or not these type-one equilibrium points lie on the stability boundary of the corresponding SEP. If the unstable manifold of a type-one equilibrium point converges to the corresponding SEP, this type-one equilibrium point is on the stability boundary of SEP.
- The type-one equilibrium point with the lowest energy function value, relative to the corresponding SEP, is the closest UEP, and the corresponding lowest energy function value is the critical energy.

Based on the above three steps, critical energies, which guarantee the transient stability, can be calculated.

III. CASE STUDIES

In this section, a test system is employed to demonstrate the performance of the proposed method. A revised IEEE 30-bus network is shown as Fig.3. The capacities of loads, except the real power at the bus 5, are 1.6 times as large as original ones. The active outputs of generators are shown in TABLE I.

According to offline analysis, one scenario of the loss of synchronism is that G1, G2 and G13 are in a group and G5, G8 and G11 are in another group. Based on this grouping scenario, possible topologies and some critical changes, e.g., clearing line 1-2 or 2-4, are identified. SEPs and closest UEPs of these possible topologies with and without critical changes can be calculated offline. Though the actual power of generators may be not exactly the same as typical operating conditions, some minor differences around typical operating conditions will not result in a significant change on dynamic characteristics of the system.

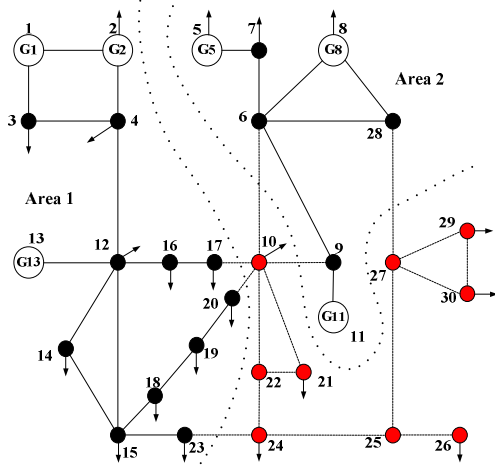


Figure 3. Diagram of the test system

TABLE I. ACTIVE OUTPUTS OF GENERATORS

	G1	G2	G5	G8	G11	G13
P(MW)	69	60	110	65	55	50

Assume that a three-phase ground-fault occurs on the line 2-4 and the fault is cleared after 0.4s. Fig.4 shows the swing trajectories of different generators. The trajectories show that the system should be separated into two areas. According to the DC power tracing method, a rough separation strategy, including the area 1 and the area 2, can be established, shown in Fig.3. The proportions of loads supported by each group are shown in TABLE II.

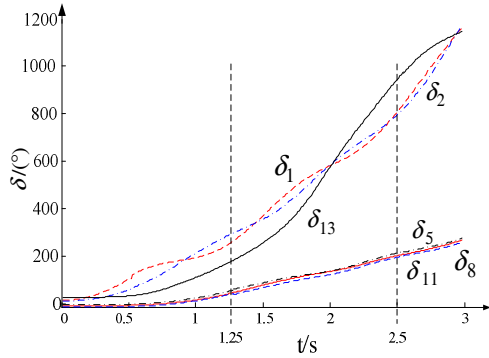


Figure 4. Swing trajectories

TABLE II. PROPORTIONS OF LOADS SUPPLIED BY EACH GROUP

Load No.	Group 1 (G1, G2, G13)	Group 2 (G5, G8, G11)
2, 3, 4, 12, 14, 15, 16, 17, 18, 19, 20, 23	100%	0
5, 8	0	100%
7	3.36%	96.64%
10	38.55%	61.45%
21	38.55%	61.45%

24	86.63%	13.37%
26	86.63%	13.37%
29	30.61%	69.39%
30	30.61%	69.39%

Though the load 7 is supplied by two groups, it is still grouped into the area 2 because of the system topology and the low proportion of power supplied by the group 1. Buses marked with red color cannot be determined to belong to which areas using the power flow method. With constraints of the system topology and the acceptable power imbalance in each area, limited separated strategies for undetermined buses can be obtained. The acceptable power imbalance of each area is set to 20MW. The possible strategies for undetermined buses are shown as TABLE III.

TABLE III. POSSIBLE STRATEGIES FOR UNDETERMINED BUSES

Scheme	Group 1	Group 2	Splitting Lines	Priority
1	10 21	24 26 29 30	6-10, 9-10, 22-24, 23-24	4
2	21 24	10 26 29 30	10-17, 10-20, 10-22, 10-21, 24-25	2
3	10 21 24 26	29 30	6-10, 9-10, 25-27	5
4	24 26 29 30	10 21	10-17, 10-20, 22-24, 27-28	6
5	21 24 26	10 29 30	10-17, 10-20, 10-21, 10-22, 25-27	1
6	10 21 24	26 29 30	6-10, 9-10, 24-25	3

Though the six strategies, shown in TABLE III, satisfy steady-state constraints, they may be transient instability after separation. For example, splitting the system at 2.5s according to the scheme 6 will result in the loss of synchronism in the area one. The swing trajectories are shown in Fig. 5.

Offline analysis is used to estimate critical energies of possible strategies after separation. For the given operating condition, acceptable angular values of a possible strategy can be calculated. For example, if the generator G13 is considered as the reference generator, the acceptable angular values of the generator G1 and G2 of the scheme 6 can be calculated, blue boundary shown as Fig.6. Considering different topologies of the real scenario, Fig.6 also shows the acceptable angular values with some lines being disconnected. The results show that some topology changes will not have great influences on stability boundaries estimated by the CUEP method.

In real operating conditions, the demand of each load may be around rather than be exactly equal to a certain typical scenario. Fig.7 shows the stability boundaries with 90% and 110% load demand levels compared with a typical scenario. The results show that fluctuations around a typical scenario actually will not greatly influence the stability boundary.

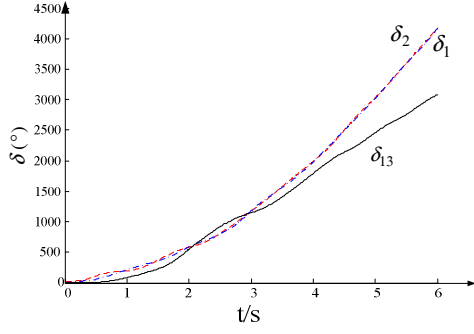


Figure 5. Swing trajectories

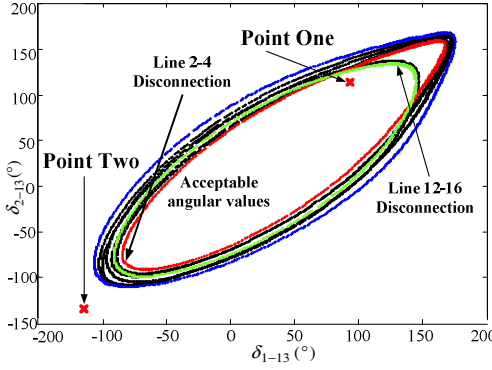


Figure 6. Estimated stability boundary with different topology changes

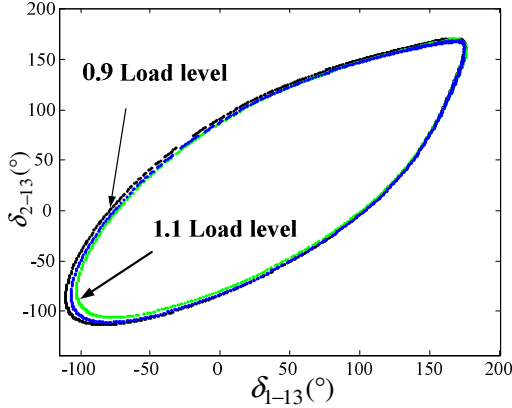


Figure 7. Estimated stability boundary with different load levels

According to the above analysis, some minor around typical scenarios changes may not have a great influence on stability boundaries calculated by the closest UEP method. Therefore, in the real system, approximate stability boundary for typical scenarios can be calculated in advance. Then, rotor angles, provided by PMUs, are checked whether or not they are in the stable region. For example, at time 1.25s, $\delta_{1-13} = 91.2^\circ$ and $\delta_{2-13} = 121.5^\circ$ (shown as Fig.4) are in the

stability region (shown as **Point One**). If the system is separated at this time, the separated systems will be transient stability. However, at time 2.5s, $\delta_{1-13} = -136.2^\circ$ and $\delta_{2-13} = -139^\circ$ (shown as **Point Two**) are not in the stability region. It shows that the strategy is transient stability if splitting at time 2.5s. Similarly, other strategies can be checked using the same method. If splitting at time 1.5, all strategies, in TABLE III, are feasible. In this case, the one with the higher priority is selected as the final splitting strategy. If splitting at time 2.5, the schemes 1, 2 and 5 are transient stability.

IV. CONCLUSIONS

A systematic controlled separation with three steps is proposed to cover steady-state and dynamic constraints with PMU measurements. At the first step, the power flow tracing method is employed to determine rough separation strategies. At the second step, the buses cannot be covered at the first step will be analyzed with steady-state constraints. At the third step, transient stability of separated areas is checked based on information provided by PMUs. The final controlled separation strategies are identified with steady-state and dynamic constraints. A test system is shown to validate the proposed method.

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